Space Agriculture: Evolution of Plant Growth Technologies

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In Space, explorers need *in situ* Food Production

- Enables colonization of space
  - **Sustainable:** minimize logistics of resupply
  - **Supplies:** Light, CO$_2$, O$_2$, Nutrients, Water, Soil
  - **Crew Psychological well-being:** green Earth
NASA’s Bioregenerative Life Support Testing

**CELSS Program**
- Wheat
- Rice
- Dwarf Grain and Vegetable Cultivars (Utah State)
- Algae
- Closed Systems
- Salad Machine

**ALS Program**
- Sweetpotato
- Peanut (Tuskegee)
- Lettuce
- Potato (Wisconsin)
- Soybean (North Carolina State)
- Nitrogen Nutrition (UC Davis)
- Lettuce (Purdue)
- STS-73 Potato Leaves
- Rutgers NSCORT Tomato
- Purdue NSCORT Cowpea Rice
- ISS Wheat

**Universities**
- ARC
- Rutgers NSCORT
- ARC
- Purdue NSCORT
- ARC
- MIR Wheat Studies
- ARC
- Never Completed

**NASA Centers**
- KSC
- NFT Lighting CO₂ Studies Waste Recycling Salad Crops
- JSC
- Solid Media Atm. Pressure Human / Integration
- LMLSTP BIO-Plex

Most activities terminated ca. 2006-2007
Salad Machine—Transit / Orbit

• Scale – Expand from Experimental to Production
  • 300 g/d = daily: 50 g salad for Crew of 6
  • 1 m² Planting area

• Performance criteria:
  • Productivity – maximize
  • Consistency – robust, repeatable
  • Crew Time – minimal

• Spacecraft
  • Cabin air – CO₂, VOCs
  • Limited Power & Volume
  • Microgravity Effects
  • Water load to ECLSS
The absence of gravity induces a number of physical effects that alter the microenvironment surrounding plants and their organs. These effects include increased boundary layers surrounding plant organs and the absence of convective mixing of atmospheric gases. In addition, altered behavior of liquids and gases is responsible for phase separation and for dominance of capillary forces in the absence of gravitational forces.
Plant Growth Systems in Space

Salyut Space Stations
- Oasis Series
- Vazon
- Malachite
- Biogravistat/Magnetobiosat
- Svetoelok
- Phyton Series

Mir
- SVET
- SVET-GEMS
- Vazon
- Svetoelok
- Astroelok

Space Shuttle
- Plant Growth Unit (PGU)
- Plant Growth Facility (PGF)
- Astroelok
- Plant Generic Bioprocessing Apparatus (PGBA)

International Space Station (ISS)
- Advanced Astroelok (ADVASC)
- Biomass Production System (BPS)
- Lada
- European Modular Cultivation System (EMCS)
- Plant Experiment Unit (PEU)
- Advanced Biological Research System (ABRS)
- VEGGIE

Plant Growth Systems in Space

Plant Growth Systems in Space


### Table 2
Detailed information on the nutrient delivery systems used in flown plant growth chambers.

<table>
<thead>
<tr>
<th>Nutrient delivery subsystem</th>
<th>Oasis 1</th>
<th>Oasis 1M</th>
<th>Oasis 1AM</th>
<th>Oasis 1A</th>
<th>Vazon</th>
<th>Malachite</th>
<th>Biogravistat/</th>
<th>Magnetobiotat</th>
<th>Svetoblok</th>
<th>Phyton</th>
<th>SVET</th>
<th>SVET-GEMS</th>
<th>PCG</th>
<th>ASC</th>
<th>PGBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two compartment system (water and ion exchange resin)</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Fibrous ion exchange medium</td>
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<td>yes</td>
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<td>yes</td>
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<td>Cloth ion exchange medium</td>
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<tr>
<td>Included root zone aeration system</td>
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<td>yes</td>
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<tr>
<td>Cloth sack filled with ion exchange resin</td>
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<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Iion exchange resin, water supply</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
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<tr>
<td>n.a.</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
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</tr>
<tr>
<td>Agar based, later also used other media</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
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<tr>
<td>1.5% agar nutrient medium</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Polyvinyl formal foam surrounded perforated tubing wrapped in a wick within zeolite based substrate enriched with nutrients</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Similar to SVET but with additional sensors</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Passive system capable of containing varied substrates/materials</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Porous tubes in matrix</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Porous tubes in matrix</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Perforated tubing wrapped in a wick within a matrix</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Water reservoir providing water to experiment unique nutrient delivery equipment</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Rock wool fed by integrated water line</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
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<td>yes</td>
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<td>yes</td>
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<tr>
<td>Experiment specific</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Passive NDS, rooting pillows, manual water and nutrient supply</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

### Table 4
Detailed information on the atmosphere management systems used in flown plant growth chambers.

<table>
<thead>
<tr>
<th>Temperature and humidity control</th>
<th>Oasis 1</th>
<th>Oasis 1M</th>
<th>Oasis 1AM</th>
<th>Oasis 1A</th>
<th>Vazon</th>
<th>Malachite</th>
<th>Biogravistat/</th>
<th>Magnetobiotat</th>
<th>Svetoblok</th>
<th>Phyton</th>
<th>SVET</th>
<th>SVET-GEMS</th>
<th>PCG</th>
<th>PGF</th>
<th>PGBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ control</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Trace gas control</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

* First integrated for ASC-3 mission.

* First integrated for ASC-6 mission.
Plant Growth Systems in Space

“A single experiment in space, carried out by a given team, may well produce results that are in themselves only marginally valuable. Follow-up studies can be most helpful.”

F.B. Salisbury - 2003

Researchers Achieve Breakthrough by Growing Plants from “Seed to Seed” in Space

Researchers led by NASA-supported investigator Mary E. Musgrave have succeeded in growing plants through a full life cycle—from seed to seed—in space, demonstrating that gravity is not required for plants to reproduce. The experiments were conducted aboard the Russian space station Mir by the first “farmer in space,” astronaut C. Michael Foale.

Table 5. Summary of experiments on early reproductive development in Arabidopsis thaliana (Chromex-03, -04, and -05) on STS-54, STS-51 and STS-68

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Duration</th>
<th>Chamber configuration</th>
<th>Early reproduction</th>
<th>Pollination/seeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromex-03</td>
<td>6 days</td>
<td>Sealed chambers</td>
<td>Pollen and embryo sac aborted</td>
<td>Pollen non-viable&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Chromex-04</td>
<td>10 days</td>
<td>Sealed chambers + CO2</td>
<td>Androecium and gyroecium normal</td>
<td>No pollen transfer&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Chromex-05</td>
<td>11 days</td>
<td>Continuous air flow</td>
<td>Androecium and gyroecium normal</td>
<td>Normal&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> As determined post-flight by fluorescein diacetate staining. Refer to Kuang et al. (1995) for complete details on reproductive development in these plants.

<sup>b</sup> As determined post-flight by scanning and transmission electron microscopy. Refer to Kuang et al. (1996a) for complete details on reproductive development in these plants.

<sup>c</sup> Refer to Kuang et al. (1996b) and Musgrave et al. (1997) for details.
APH Science Carrier

• The Science Carrier (SC) is an instrumented 0.2 m² root module within the Growth Chamber.
APH Science Carrier (SC)

• The SC root tray is divided into four quadrants. Each quadrant contains the growth media, fertilizer, and water. Water is supplied from APH through four porous tubes connected to a manifold.
Scaling Food Production Systems: Media Mass

Growth Media - problems
• Bulky – containment, aeration
• Multiple plantings – loss of productivity
• Fungal growth – plant & crew health

Salads – 30 d cycles
5cm deep modules
12 plantings/year

<table>
<thead>
<tr>
<th>Media</th>
<th>Advanced Plant Habitat</th>
<th>Salad Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area</td>
<td>0.2</td>
</tr>
<tr>
<td>Granular</td>
<td>Mass</td>
<td>6</td>
</tr>
<tr>
<td>1 year</td>
<td>72</td>
<td>360</td>
</tr>
</tbody>
</table>
Future Work – Exploration

• Optimize to prevent secondary effects of microgravity
• Provide Nutrients – Obtain from waste
• Reduce Consumables – Media must be reusable